MIT

10p

UNPUBLISHED PRELIMINARY DATA

[redacted]

[redacted]

RESEARCH ON VIBRATORY-OUTPUT ANGULAR MOTION SENSORS

~~Report ESL-SR-189~~
~~M.I.T. Project DSR 9459~~
Fifth Status Report,

1 June ~~through~~ 30 November 1963

NASA ~~Research~~ Grant ~~No.~~ NsG-149-61 (NASA CR-55537; ESL-SR-189)

Prepared by Project Staff

George C. Newton, Jr. et al

31 December 1963

10 p ref

5545009

1. GENERAL

This status report covers research carried out by personnel of the Electronic Systems Laboratory, Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge 39, Massachusetts during the period 1 June through 30 November 1963 under Research Grant No. NsG-149-61 of the National Aeronautics and Space Administration. Work in the areas of experimental evaluation of rotary double modulation and feedback suppression of cross-coupled signals, described in the research proposal submitted 18 April 1963,[1] has continued. Work has been initiated on an all vibratory type gyroscope in which double modulation is accomplished by vibration rather than rotation. The results obtained on the double modulated tuning fork instrument have been very favorable and if similar improvements can be obtained with vibratory double modulation it may be possible to construct an inexpensive, low-power reliable all-vibratory gyroscope with a zero rate well below one earth's rate. The following sections briefly describe the results to date, indicate problems which have arisen and some of their solutions, describe research documentation status to date and present the financial status of the project.

2. SUMMARY OF CONTINUED RESEARCH

a. Introduction

The research conducted during this reporting period departed

---

[1] Superscripts refer to numbered items in the List of References.

N65 16986 (ACCESSION NUMBER)
10 (PAGES)
CR 55537 (NASA CR OR TMX OR AD NUMBER)
1 (THRU)
14 (CODE)
(CATEGORY)
FACILITY FORM 602

GPO
OTS
HC 1.00
MF .50

slightly from the program outlined in the proposal submitted 18 April 1963. Experimental data obtained from the rotary double modulation experiment showed that the performance of the tuning fork instrument being investigated was improved by at least two order of magnitude by double modulation. The noise contributed by the bearings in this experiment was not a limiting factor but it was larger than anticipated. These facts together with the general lack of interest in instruments employing bearings of any kind for space applications have made it desirable to investigate configurations which can be double modulated by means of vibration. Therefore, work has been resumed on vibratory fluid devices in an effort to find a basic single-axis sensor that can be double modulated through vibration rather than rotation.

The research conducted during this reporting period is outlined in the following sections.

b. Tuning Fork Gyroscope Employing Rotary Double Modulation

Good experimental data on the tuning fork instrument were finally obtained during this reporting period. The data supports the theoretical work done on double modulation and show that double modulation improves the performance of the tuning fork instrument by at least two orders of magnitude. These data and some theoretical discussion of double modulation and the instrument being investigated are contained in a paper entitled "Reduction of Errors in Vibratory Gyroscopes by Double Modulation" by R.W. Bush and G.C. Newton, Jr. This paper was presented at the Unconventional Inertial Sensors Symposium, November 18, 1963, at Republic Aviation Corporation. Twenty five copies are included with this Status Report.

Research is continuing on the tuning fork instrument in order to obtain more complete comparison data on the performance with and without double modulation and also to investigate sources of the zero-rate drift with double modulation. It is expected that many of the sources of error will be the same with vibratory double modulation as with rotary methods. Research in this area is both experimental and theoretical and is directed toward extracting the maximum amount of experimental information from the present equipment. The data obtained to date on the tuning fork instrument have pointed out several areas which need to be investigated. Although the magnitude of the zero-rate signal was reduced from 5650 eru to 60 eru by double modulation, only 40 eru of the 60 could be attributed to the acceleration of gravity. This rather large number (40 eru) is characteristic of tuning fork instruments and is larger than theory indicates for other symmetrical drive configurations. The source of the remaining 20 eru of zero rate signal is the subject of continuing research. Possible sources under investigation are complex gravity distortions, bearings, and the signal processing electronics.

All of the above-mentioned experiments have been conducted with the double-modulation cage assembly mounted in tapered roller bearings. In addition to this type of bearing, the original plans called for tests with ball bearings and fluid-lubricated journal bearings in order to assess the effects of bearing noise more fully.

Conical journal bearings have been installed and tested during this report period. Because of incompletely understood distortions of the cage assembly, the expected bearing noise reduction has not been realized but rather the opposite. The conical bearings have a noise spectrum associated with them which has large spikes at harmonics of the spin frequency and it is therefore necessary to align the instrument output frequency between two spin-frequency harmonics. Even when this is done the noise at the output of the double modulated instrument is twenty times larger than the tuning fork unbalance noise. Because this is an unacceptable condition reworking of the cage assembly and installation of ball bearings is planned for the next period. Although ball bearings in the sizes available are not the optimum support means, they should be adequate for the completion of the rotary double modulation experiment. The noise requirement is not nearly as critical as in conventional gyroscopes and we desire only bearings with consistent characteristics which can handle the unbalance and normal gyroscopic forces exerted by the rotor. The tapered roller bearings initially used were excessively noisy since they were designed for much greater loads.

Another source of noise in the experiment is the signal processing electronics. Reference 2 cites cross-coupling as a source of zero-rate signal and presents a theoretical treatment of the effect for an instrument without double modulation. Ideally, the double modulation process eliminates zero-rate signals associated with acceleration-independent cross coupling. However, the experimental vibratory gyroscope, when doubly modulated, exhibits excessive stochastic zero-rate output (noise). An analytical and experimental investigation of the source of this noise was initiated during this report period.

It is clear that the ultimate source of the stochastic zero-rate output is the random vibrational energy developed when the tuning fork package is spun at the double modulation frequency. There appears to be two paths whereby this energy is most easily coupled into the signal processing chain. One path is directly through the output vibration pickup and the second is through the tuning fork **reference** signal pickup. In the first path the noise signal comes from the bearings through the resonant system suspension. In the second path, the noise is caused by random relative motion between the tuning fork and the reference pick up coils. The resultant perturbation of the reference signal introduces output noise at the demodulator used to remove the double-modulation spin frequency.

An analysis of the demodulation process in the presence of the above corrupting signals has been completed. The most significant result of the analysis is the prediction of a slowly varying (quasi d-c) output superposed upon the previously predicted zero-rate signal.

During the last days of this report period an experimental program aimed at verifying the above analysis was undertaken. In order to determine separately the presence of each postulated noise source the experimental work was broken into two parts. The first consisted of a determination of the spectrum of the signal at the output vibration pickup during double modulation. In the second part a sinusoidal signal was demodulated by a reference signal corrupted with a periodic perturbation and the spectrum of the demodulator output was recorded.

The raw data from these experiments is presently under analysis. Results should be available early in the next reporting period.

Zero rate errors due to complex gravity distortions are also possible. Some time will be spent investigating this possibility; however, since the sources are different for different drive configurations, a detailed examination is hardly worthwhile.

c. Feedback Suppression of Cross-Coupled Signals

Work has continued on developing a practical filter theory for suppressed-carrier systems as described in the previous status report.[3] Straight application of the time-varying linear filter theory with the mean-square error criterion yields filters which are not very practical because harmonic and quadrature errors are weighted equally with message errors. Therefore the practical demodulator problem must be taken into consideration and the error criterion modified so that the systems which result and the minimized error are more realistic. In this manner filters before and after the demodulator and the demodulator itself can be optimized taking into account instability in the carrier frequency as well as saturation and fixed element constraints in the system.

Emphasis on the actual suppression of cross-coupled signals through feedback has been reduced because of the following:

1. Work on tuning fork instruments at Farnborough[3] has demonstrated that precision balancing of vibratory drive mechanisms can be accomplished.

2. Bearing noise associated with the double modulation motion is larger than expected and presently larger than the magnitude of the cross-coupled vibrations. Thus reduction of bearing noise effects should have first priority.

3. Work has been initiated on distributed parameter drive methods in which cross-coupling arises from sources other than mass unbalance and can be reduced to acceptable levels by symmetric drive arrangements.

d. Vibratory Angular Motion Sensors Using Fluids

A renewed interest in angular motion sensors using fluids has occurred for two reasons. First, space applications of gyroscopic devices place emphasis on low power consumption, reliability, and long life, even more than on extreme performance as measured in terms of sensitivity, drift, and freedom from acceleration errors. Second, during the reporting period, one of the project staff members, Professor G.C. Newton, Jr., met Mr. C.E. Granqvist in Sweden and thereby obtained new information about a vibrating gas particle gyroscope described in Reference 5. This information appeared to resolve some of the questions raised in Reference 4 and indicated that renewed activity in this area is likely to be worthwhile.

The object of the current studies of vibratory fluid sensors is to ascertain more clearly what the prospects are for these devices in relationship to space **application**. This is to be done both from the viewpoint of a simple instrument without double modulation as well as from the viewpoint of a more precise instrument employing double modulation. Hopefully, a vibratory fluid sensor could be made in smaller physical size than a solid vibrating device such as a tuning fork. This size reduction of the basic single-axis sensor would make possible a vibratory form of double modulation thereby eliminating the need for bearings.

The investigation of vibratory fluid sensors involves both analytical and experimental aspects. The analytical work is concerned with choice of fluid, configuration, and driving and sensing means. In parallel with these studies an experimental program has been undertaken with a view of confirming Granqvist's statements concerning the performance which **he** has observed or a particular half-wave resonator configuration using air as the fluid.

On the basis of Granqvist's statement concerning his experiments, a performance level of one earth rate drift and a sensitivity of the order of one earth rate should be relatively easy to obtain. The first crude experiment failed to confirm these hopes. Therefore a second, slightly more refined, version has been constructed in the form of Fig. 2.1. By means of the

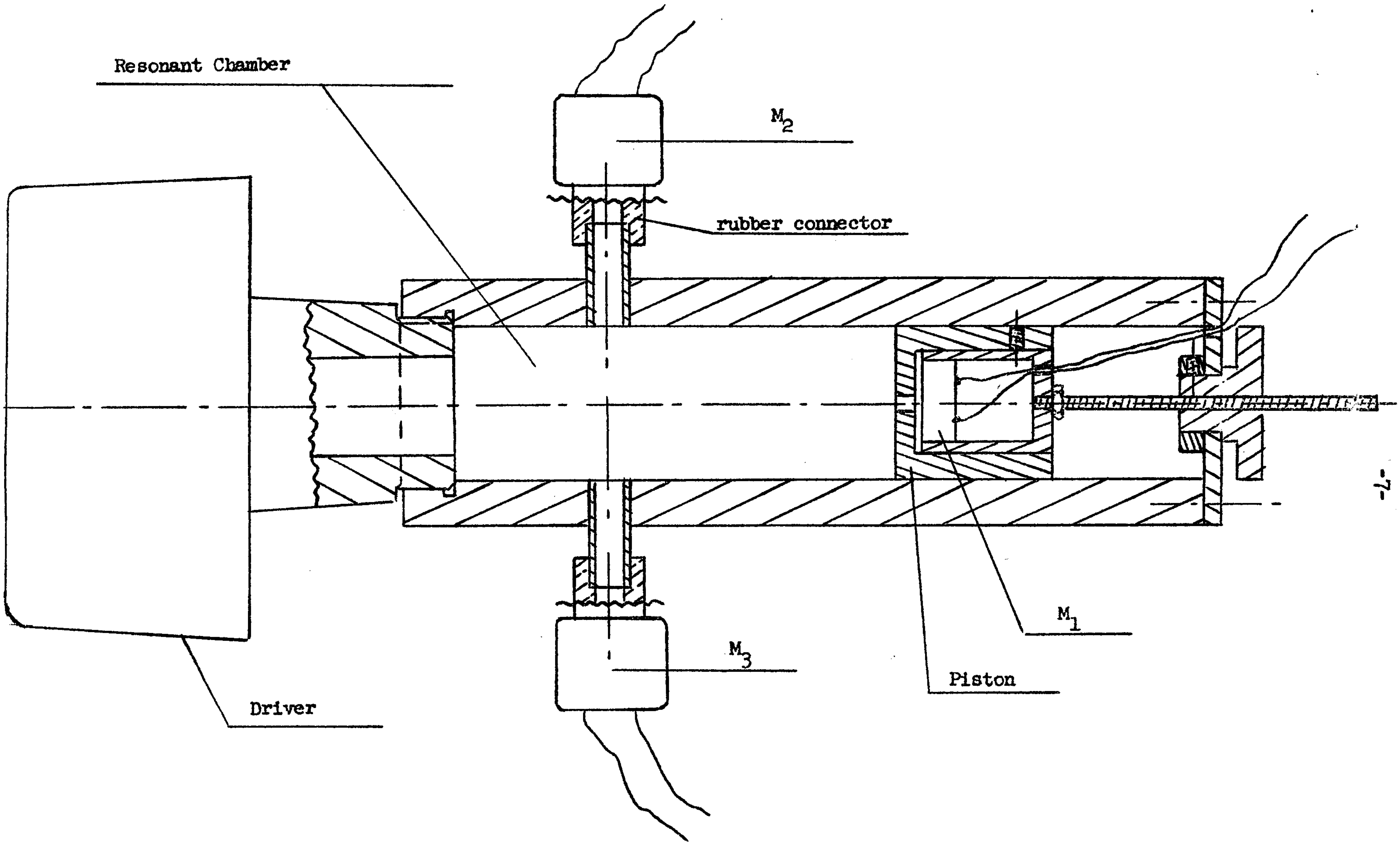

Fig. 2.1 Second Form of Vibrating Fluid Angular Motion Sensor

driver located at one end of a half-wave resonator chamber a velocity anti-node is established in the vicinity of microphones M_2 and M_3. The application of an angular rate about an axis perpendicular to the plane of the paper produces a Coriolis pressure that should be measureable by means of these microphones. The piston, which serves as a reflector, is adjusted to minimize the driving wave pressure at the sensing microphones. A monitoring microphone M_1 is provided at the piston for making acoustical measurements.

On the basis of the experiments conducted so far on the apparatus of Fig. 2.1 we have learned that it is rather difficult to know the driving wave pressure in the vicinity of the microphones M_2 and M_3 by adjustment of the piston because of the relatively low Q's that seem to be characteristic of acoustical resonators and also because of large second harmonic waves, presumably set up by distortions introduced by the driver. Nevertheless, solutions are foreseen for many of these problems and additional experiments are planned with improved forms of apparatus.

3. PROJECT DOCUMENT STATUS

During this reporting period the following manuscript was submitted to the Institute of Electrical and Electronic Engineers for presentation at the 1964 Joint Automatic Control Conference:

"Reduction of Errors in Vibratory Gyroscopes by Double Modulation" by R.W. Bush and G.C. Newton, Jr.

4. BUDGET STATUS

As of 30 November, 58 per cent of the total Grant funds have been expended in a time corresponding to 68 per cent of the Grant period.

5. ANTICIPATED FUTURE RESEARCH

Future research will concentrate on the completion of the double modulation experiment using the tuning fork gyroscope and further evaluation of the prospects for vibratory fluid devices. Details of plans are included in the review of Continued Research of Section 2.

6. PROJECT STAFF

The following research staff members contributed to this project during this reporting period.

Prof. George C. Newton, Jr., faculty supervisor (part time)

Richard W. Bush, full time staff until September, research assistant thereafter

Jean C. Lavigne, full time staff member (since September)

Joseph A. D'Appolito, research assistant

William Kleinhans, research assistant (June only)

Robert W. Rasche, full time staff member until September

Approved by: George C. Newton, Jr.

George C. Newton, Jr.
Associate Director
Electronic Systems Laboratory

31 December 1963

REFERENCES

1. "Proposal for Research on Vibratory-Output Angular Motion Sensors", Electronic Systems Laboratory, Massachusetts Institute of Technology, 18 April 1963

2. "Reduction of Errors in Vibratory Gyroscopes by Double Modulation" by G.C. Newton, Jr. and R.W. Bush, Electronic Systems Laboratory, Massachusetts Institute of Technology, 1964

3. "Research on Vibratory-Output Angular Motion Sensors, Fourth Status Report", Electronic Systems Laboratory, Massachusetts Institute of Technology, 1 June 1963

4. "A Vibratory Acoustic Gyroscope" by R. Swerdlow and J.G. Whitman, Electronic Systems Laboratory, Massachusetts Institute of Technology, Report #ESL-TM-162, December 1962

5. "Gyroscope Device with Vibrating Gas Particles or Particles of Another Transferring Medium" by C.E. Granqvist U.S. Patent No. 2,999,389